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The 200 MWt nuclear heating reactor and its possible application in seawater desalination

Dazhong Wang, Duo Dong, Wenxiang Zheng, Dafang Zhang, and Lihua Wang

Institute of Nuclear Energy Technology (INET), Tsinghua University, Beijing 100084 (China)

SUMMARY

The 200 MWt nuclear heating reactor (NHR-200) is designed with a number of advanced and innovative features, including integrated arrangement, natural circulation, self-pressurized performance, hydraulic control rod drive and passive safety systems. The NHR-200 can serve as a safe and economic energy source for seawater desalination. This paper will cover the development status, main design and safety features of the NHR-200 as well as the solutions for coupling the NHR-200 with the seawater desalination process.

INTRODUCTION

Energy supply has been one of the major issues impacting highly on the socio-economic development of China. As its energy system is characterized with the predominance of coal consumption and the distribution of the coal resources is quite uneven, many industry and population centers have suffered from energy shortage and overburden on coal transportation in addition to the environmental pollution caused by massive coal burning. In order to resolve the above problems, the R&D of the nuclear heating reactor (NHR) has been conducted as one of national

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key projects in science and technology in China since the 1980 s. The following arguments also favour the development of the NHR in China.

(1) Potential market for the NHR is quite broad. Among other things, space heating and low temperature process steam generation account for about 25% of total primary energy consumption.
(2) Design and construction of the NHR can be mostly based on the present-day domestic technology.

Research work on possible application of nuclear heat was initiated in the early eighties. During 1983–1984, the INET used its existing pool type reactor to provide space heat for the nearby buildings. Based on the heating grid conditions in China and the comparisons among various design concepts of the NHR, the vessel type NHR has been selected as a main development direction. As a result, construction of a 5 MWt experimental NHR (NHR-5) started at INET in 1986. The reactor was completed in 1989 and has been operated successfully for space heating since then.

In order to investigate the comprehensive uses of the NHR, some experiments, such as electricity generation with low pressure steam under cogeneration mode and the air-conditioning for a large building area by using the lithium-bromide absorption process, have been performed at the NHR-5, and the nuclear seawater desalination experiment is under way.

With its excellent performance proven, the NHR has made a great impression on Chinese society. Up to now, nearly 20 cities and utilities are very interested in introducing the NHR into their local energy system. Therefore, the commercial sized NHR with an output of 200 MWt (NHR-200) has been developed by INET. For speeding up the process, it has been decided to build a NHR-200 demonstration plant in Northeast China in 1994. The feasibility study and basic design for the NHR-200 project have been finished and approved by the respective authorities, and its detailed design is being carried out at present.

The permissibility study on nuclear desalination shows that it is feasible to use nuclear energy as a substitute energy for desalination from the point of view of technology, economic and environmental protection. Nuclear desalination will have a bright future. The NHR-200 is suitable for heat source of small–medium size desalination plant with regards to technical parameters and safety.

It is expected that the first NHR-200 will be put into operation in 1998 and several 2x200 MWt nuclear heating plants could be constructed in China in the late 1990 s. The prospect for developing the NHR looks rather promising.

TECHNICAL DESCRIPTION OF THE NHR-200

The NHR-200 is developed upon the experience gained from the design, construction and operation of the NHR-5. It has been designed with a number of the advanced and innovative features, which distinguish it fundamentally from the present-day nuclear power plant.

Figs. 1 and 2 show the reactor structures and core cross section of the NHR-200 respectively. It is a vessel type light water reactor with the integrated arrangement, natural circulation, self-pressurized performance and dual vessel structure. The reactor can be operated under pressurized condition or slight boiling condition. The core is located at the bottom of the reactor pressure vessel (RPV). The primary heat exchangers (PHEs), equipped with "U" type tube bundles for easy in-site repair, are arranged on the periphery in upper part of the RPV. The system pressure is maintained by inert gas and/or steam. A containment fits tightly around the RPV so that the core will not become uncovered under any postulated coolant leakage within it. Reactor coolant is circulated by density differences between "hot" and "cold" region inside the RPV. There is a long riser on the core outlet to enlarge natural circulation capacity.

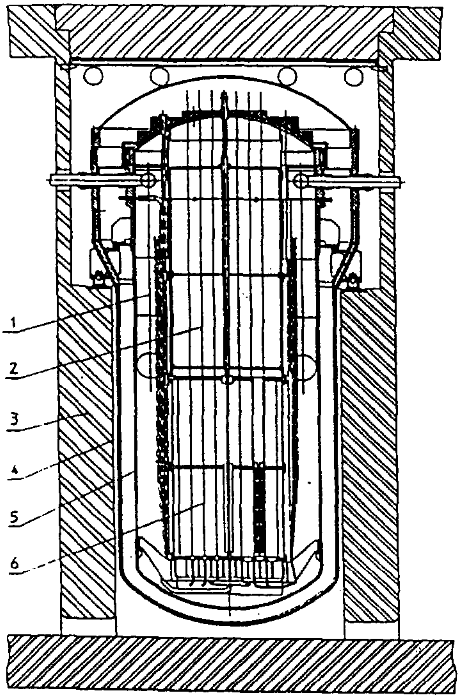
Gadolinium oxide as a burnable poison is used to control the reactivity along with the BC control rods. The reactor coolant does not contain boron acid during normal operation.

A hydraulic control rod drive system is adopted in the NHR-200, which is designed on a "fail-safe" principle, i.e. control rods will drop into reactor core automatically under lose of power supply, depressurization, pipe break and pump shut down events.

Spent fuel assemblies are stored in the racks around the active core. This solution greatly simplifies the refueling equipment and eliminates the necessary space in the reactor building.

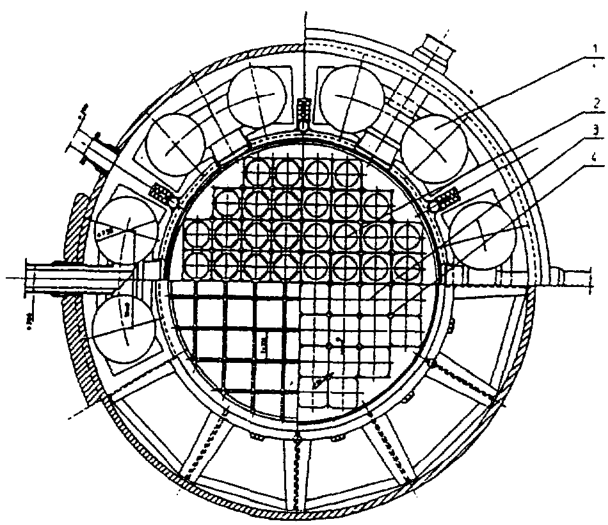
A simplified schematic diagram of the NHR-200 is shown in Fig. 3. The nuclear heat supply system (NHSS) contains triple loops. Primary coolant absorbs heat from reactor core, then passes through riser and enters the PHEs, where heat carried is transferred to the intermediate circuits. Finally, heat is delivered to heating grid via the intermediate heat exchangers. An intermediate circuit is needed in the NHR to keep heating grid free of radioactivity.

There is no emergency core cooling system in the NHR. The residual heat removal system (RHRS) is the most important safety system of the NHR; it is designed with a passive pattern. The decay heat will be dispersed into extreme heat sink by natural circulation.



1. Primary heat exchanger, 2. Riser, 3. Biological shield, 4. Containment
5. Pressure vessel, 6. Core

Fig. 1. The NHR-200 reactor.



1. Primary heat exchanger, 2. Riser, 3. Fuel assemble, 4. Control rod

Fig. 2. Core arrangement.

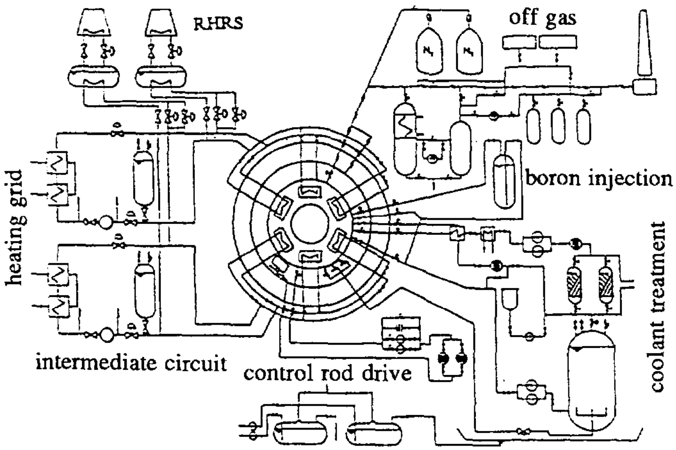


Fig. 3. Schematic system diagram.

A boron acid injection system, as a secondary reactor shutdown system, will be operated by gravity when anticipated transient without scram (ATWS) occurs.

The NHSS and its all auxiliary systems, including the rad-waste processing systems, are housed in one building complex.

The key design data for primary system can be found in Table I, while operating parameter in the intermediate circuit may be varied with the different purposes. Table II presents a comparison of the main design features between the NHR and a present-day PWR.

SAFETY CONCEPTS AND FEATURES OF THE NHR-200

The safety concepts of the NHR are fundamentally based on its excellent inherent characteristics and passive safety instead of the engineered safety features.

The NHR is operated under low pressure, low temperature, low power density and low radioactivity content in primary coolant. The huge subcooled water inventory results in a high thermal inertia in the primary system. A large negative temperature reactivity coefficient has been achieved in the core nuclear design. Meanwhile the innovative hydraulic

TABLE I

Main design data of NHR-200

Operating mode	PWR		BWR
Thermal power, MW		200	
Primary system pres., MPa		2.5	
Core inlet/outlet temp., °C	150/210		193/224
Average linear heat rate, kW/m		7.67	
Volumetric power density, kW/l		36.2	
Number of fuel assemblies		96	
Number of control rods		32	
Active core height, m		1.9	
Active core diameter, m		1.9	
Inventory of UO_2, t		14.87	
Enrichment of initial core, %		1.8/2.4/3.0	
Refueling enrichment, %		3	
RPV diameter/height, m		5.0/13.6	
PHE numbers		6	

TABLE II

Comparison of main design features between NHR and PWR

Technical feature	NHR	PWR
Primary system arrangement	Integral	Separate
Mode of pressurization in primary system	Self-pressurized	Pressurizer Heater+spray
Mode of circulation of reactor coolant	Full power natural circulation	Forced circulation
Safety systems	Passive	Active
Control rod drive	Dynamic-hydraulic	Motor-mechanic
Spent fuel storage	Inside RPV	Outside RPV
Emergency core cooling	No	Multiple systems
Containment spray and cooling system	No	Yes
Born solution system for reactivity control	No	Yes
Diesel engine	Non-safety class	Safety class
Component cooling, plant service water system	Non-safety class	Safety class (partial)
Ventilation system	Non-safety class	Safety class (partial)

control rod drive mechanism and a great inertia in the plant lead to exclude the rod ejection event and any other large uncontrolled reactivity additions. Therefore any transients and accidents can be very well counteracted. The core decay heat is transferred into the atmosphere by natural circulation. This makes core cooling more reliable. Moreover, the integrated arrangement, low operating pressure, low neutron fluence to the RPV and all in-vessel penetrations (only with small diameter) located on the upper of the RPV lead to a low probability and less seriousness of the loss of coolant accident. The loss of primary coolant is limited to the content that the core will never be uncovered, so the emergency core cooling system is not necessary for the NHR.

The intensive safety analyses have been conducted to evaluate the overall performance of the NHR-200. The results from the analyses of any design basis accidents are summarized as follows:

(1) DNBRmin is always greater than the safe limit. The fuel element claddings are not overheated and damaged.
(2) Peak pressure in the primary system is far below its design pressure and the integrity of coolant pressure boundary will maintain properly. The safety valve on the RPV will not open until "loss of main heat sink ATWS" occurs.
(3) Reactor core will never be uncovered. The proper fuel cooling is ensured.
(4) Maximum fuel enthalpy is much lower than the safe limit.
(5) Release of radioactivity is much less than the prescribed limit.

The analyses on beyond design based accidents have also been performed. Fig. 4 presents the NHR-200 responses during a loss of the main heat sink-ATWS followed by a failure in the boron acid injection system. As seen in the figure, after the safety valve opens and closes in several cycles, the reactor power is smaller than the capacity of a RHRS.

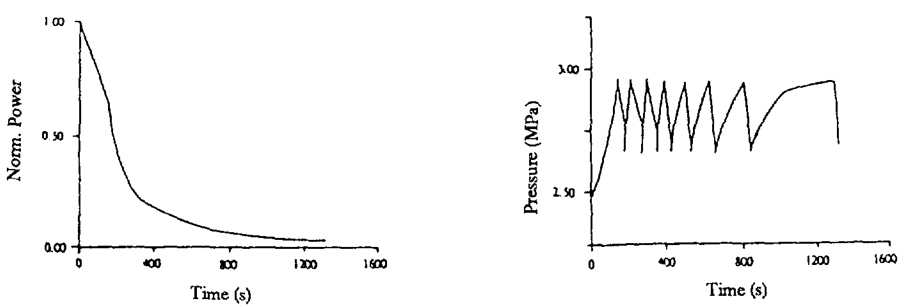
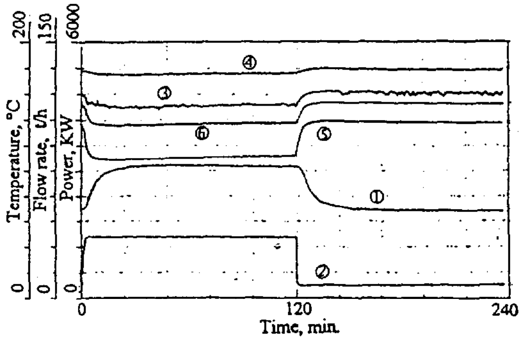


Fig. 4. Reactor power and pressure in loss of main heat sink – ATWS without boron injection.

The transient during a hypothetical crack at the bottom of the RPV has been analyzed. Primary coolant discharge into containment is terminated due to pressure balance between the two vessels, and reactor core is still kept under coolant. The most serious accident would be a total loss of all heat sinks, which means that the core decay heat can just be removed by steam discharge from the primary system via a safety valve. The analytical results show that the core will not become uncovered until about 52 hours after the accident occurs. The grace period is long enough for operator to take corrective action to prevent the core from being uncovered.

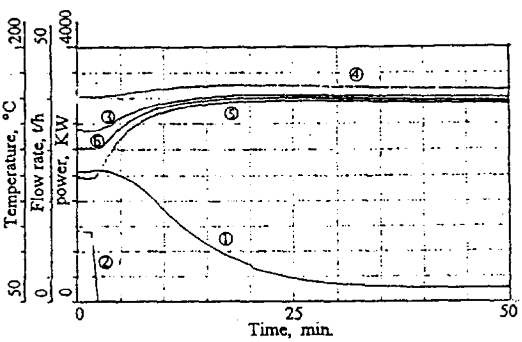
The probability study has been carried out to assess the reliability of the NHR-200 systems and the probability of a core melt with a subsequent massive release of radioactivity. The results have indicated again that a core melt down would be excluded.

The overall excellent safety characteristics of the NHR have also been demonstrated by the experimental and operational data from the NHR-5. Two examples are given herein. Fig. 5 shows the results of a load-power follow test, in which a step change in flow rate through the intermediate heat exchangers is performed to simulate load decrease or increase. The results indicate that the reactor power follows a large load change properly based on its self-regulation capacity without any operator action. Fig. 6 presents the responses of key system parameters under a loss of main heat sink-ATWS without boron injection. Owing to a large negative temperature coefficient of reactivity and a great heat capacity, the reactor power automatically decreased to a very low level, and the core outlet temperature just rose less than 5°C.



1. Reactor power, 2. Flow rate through IHE, 3. Core inlet temperature,
4. Core outlet temperature, 5. Outlet temperature in 2nd side of PHE,
6. Inlet temperature in 2nd side of PHE.

Fig. 5. Load-power follow test at NHR-5.



1. Reactor power, 2. Flow rate through IHE, 3. Core inlet temperature,
4. Core outlet temperature, 5. Outlet temperature in 2nd side of PHE,
6. Inlet temperature in 2nd side of PHE.

Fig. 6. Experiment on loss of main heat sink without shutdown.

POSSIBLE APPLICATION IN DESALINATION

The overall excellent performance of the NHR-200 indicate that the NHR-200 is suitable to the coupling with a seawater desalination plant from both technical and economic stand, and is most preferred for the region without an established infrastructure.

The report on the regional feasibility study in the Middle East and North Africa will first consider using a small-medium sized nuclear power plant as a heat source for desalination, which matches a desalination plant with a capacity of 156,000 m^3/d.

In order to obtain optimum economic viability for the nuclear desalination, several solutions for coupling the NHR-200 with a desalination plant have been studied. For the common base of evaluation, only the multi-effect distillation (MED) process was considered among the desalination technologies. The NHR-200 is suitable for heat small-medium size desalination plant. The NHR-200 nuclear desalination system consists of one unit of 200 MWt nuclear heating reactor and MED plant. Its capacity is 120,000-156,000 m^3/d.

TECHNICAL SCHEME OF THE NHR-200 NUCLEAR DESALINATION SYSTEM

Two versions of NHR-200 nuclear desalination system can be chosen. One is that the NHR-200 is only used provides the heat source of desalination plant, another is that it not only be used as the heat source of desalination plant but also to supply the electricity for consume of reactor and desalination plant. For both heat only and cogeneration versions the MED process is taken for desalination plant.

Only heat production for desalination plant

The simplified diagram of this nuclear desalination system is shown in Fig. 7. The nuclear heat is transferred through an intermediate circuit to the steam generator in which steam produced is delivered to the desalination plant. Table III lists the main parameters of this system.

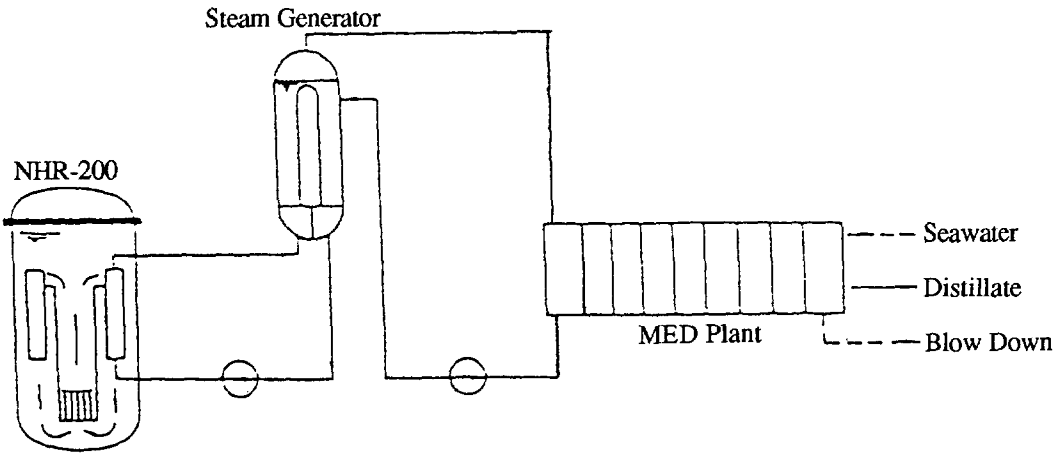


Fig. 7. Schematic diagram (heat only) of NHR-200 desalination system.

The maximum daily water production could reach up to 156,000 m^3/d if the desalination plant could take 4 units, each with a capacity of 48,000 m^3/d or 13 units, each with a capacity of 12,000 m^3/d.

TABLE III

Main parameters of NHR-200 nuclear desalination system with only heat production

Reactor power, MWt	200
Core outlet temperature, °C	210
Core inlet temperature, °C	150
Outlet temperature at intermediate circuit, °C	163
Inlet temperature at intermediate circuit, °C	135
Steam temperature, °C	130
Maximum sea water temperature, °C	120
Capacity of MED unit, m^3/d	24,000
Number of MED unit	6
GOR	20
Maximum water production, m^3/d	144,000

Cogeneration-heat and electricity production for desalination plant

For this nuclear desalination system it is necessary to install additional power conversion system to provide the electricity. The system principle diagram is showed in Fig. 8. Based on the data provided by IAEA the specific electricity consume for MED desalination plant is 0.083 $KW(e)/m^3/d$, 9.960 MW electricity is needed for desalination plant with capacity of 120,000 m^3/d. The electric consume for heating reactor is about 2 MW. In Table IV the main parameters of NHR-200 nuclear desalination system with cogeneration is listed.

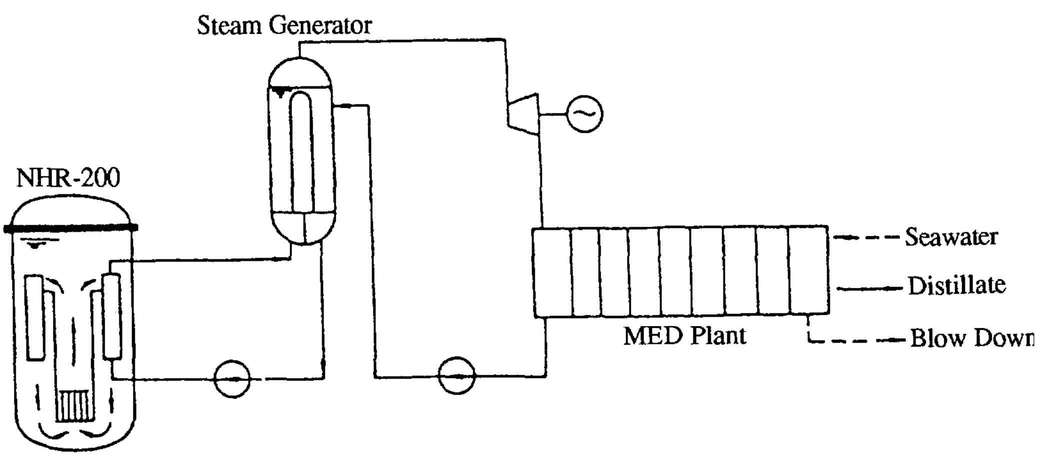


Fig. 8. Schematic diagram (cogeneration) of NHR-200 nuclear desalination system.

TABLE IV

Main parameters of NHR-200 nuclear desalination system with cogeneration

Reactor power (t), MWt	200
Core outlet temperature, °C	210
Core inlet temperature, °C	150
Outlet temperature at intermediate circuit, °C	170
Inlet temperature at intermediate circuit, °C	144
Steam temperature, °C	141
Maximum sea water temperature, °C	105
Capacity of unit, m^3/d	24,000
Number of unit	5
GOR	17
Maximum water production, m^3/d	120,000
Electricity output, MWe	12

PRELIMINARY ECONOMIC ESTIMATION

According to the cost evaluation methodology of IAEA, the investment, fuel cost as well as O & M cost of NHR-200 are estimated. The basic investment cost of NHR-200 with only heat production is 110.4 million US $ (1991, see Table V). The basic investment cost of NHR-200 with cogeneration plant is 118.4 million US $ (1991). On the basis of international fuel cost data, the first core fuel cost is 13.6 million US $ and annual fuel cost is 4.1 million US $. Table VI shows the annual operation and maintenance cost. The annual heat cost for the desalination plant is given in Table VII.

According to the input data of MED water plant, the total water production costs are estimated for the cases of 5% and 8% interest rate. The total water costs are shown in Table VIII. The water production costs are in general around 1 US $/m^3 for desalination plants combined with NHR-200.

TABLE V

NHR-200 with only heat production basic investment cost million in 1991 (million US $)

Buildings and structure at the plant site	14
Reactor plant equipment	46.9
Electrical equipment and instrumentation and control plant equipment	10.43
Miscellaneous plant equipment	5.65
Subtotal for direct costs	76.98
Engineering and design	11.75
Construction services	4.88
Other indirect costs	3.37
Subtotal for indirect costs	20
Contingencies	9.72
Owner's cost	3.7
Total basic investment cost	110.4

TABLE VI

Annual operation and maintenance cost in 1991 (million US $)

Wages and salaries for engineering and technical support staff, and operation, maintenance and administration staff	1.35
Maintenance including consumable materials and equipment	2.70
Total annual O & M cost	4.05

CONCLUSIVE REMARKS

The NHR-200 is designed with a number of advanced and innovative features, and its safety concepts are quite different from those for an electricity generating reactor. These have provided the NHR-200 with an excellent overall performance. Being a clean, safe and economic energy

TABLE VII

Preliminary economic estimation of NHR-200

	Heat only	Cogeneration
Power plant cost dada		
Spec. constr. cost, \$/kWt	552	592
Additional constr. cost, \$/kWt	55.2	59.2
Total constr. cost, \$/kWt	607.2	651.2
Construction lead time, month	48	48
Specific O & M cost, \$/MWhe	2.57	3
Specific fuel cost, \$/MWht	2.6	2.6
Levelized annual decomm. cost, M\$	0.37	0.37
Case 1 : 5% interest rate		
Total construction cost, M\$	121.44	130.24
AFUDC, M\$	12.38	13.28
Total plant investment, M\$	133.82	143.52
Levelized annual capital cost, M\$	8.7	9.32
Annual fuel cost,, M\$	4.1	4.1
Annual O & M cost, M\$	4.05	4.73
Elec. power cost, M\$/YR	0.63	0
Total annual required revenue, M\$	17.85	18.52
Case 2 : 8% interest rate		
Total construction cost, M\$	121.44	130.24
AFUDC, M\$	20.16	21.62
Levelized annual capital cost, M\$	12.57	13.5
Total annual required revenue, M\$	21.72	22.33

source, the NHR-200 can be a competent candidate for the nuclear desalination. In particular, the NHR-200 is most suitable for a desalination plant to be constructed in the area without an established infrastructure and a large grid connection. And the water production cost of NHR-200 desalination system is about 1 US \$/m^3. The thermal coupling between the NHR-200 and the MED process is rather flexible and the optimum solutions for the coupling and the water cost might be highly dependent upon the plant site specific.

TABLE VIII

Preliminary economic estimation of MED plant

	Heat only	Cogeneration
Thermal (MED) plant		
Maximum brine temperature, °C	120	105
GOR	21	17
Unit size, m^3/d	48,000	48,000
Number of unit	4	3
Annual water Prod. m^3/y	48,101,899	36,967,200
Case 1: 5% interest rate		
Water CT, fixed charge, M$ /y	20.71	15.53
Water CT, heat charge, M$ /y	17.85	18.52
Water CT, elec. charge, M$ /y	4.36	0
Water CT, O & M charge, M$ /y	5.67	4.25
Total water cost, $/m^3$	1.01	1.04
Case 2: 8% interest rate		
Thermal (MED) plant		
Water CT, fixed change, M$ /y	29.08	21.81
Water CT, heat change, M$ /y	21.72	22.33
Water CT, elec, change, M$ /y	5.45	0
Water CT, heat change, M$ /y	5.67	4.25
Total water cost, $/m^3$	1.29	1.31

Note: The desalination plant with a capacity of 120,000 m^3/d needs only 3 units, each with a capacity of 48,000 m^3/d. Therefore the investment and O & M cost for the desalination plant should be 3/4 of the one in the table.

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